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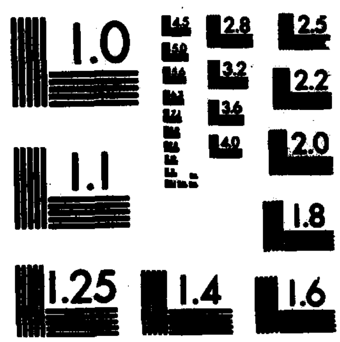

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by

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AZIMUTH DETERMINATION USING A LOW NOISE RING LASER GYRO INERTIAL MEASUREMENT UNIT

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Abstract

The performance requirements for a ring laser gyro inertial measurement system to achieve sub-arc second azimuth determination capability have been developed. Parallel theoretical studies link these requirements to identifiable laser gyro design parameters and indicate that a feasibile design could be implemented within practical constraints. A feasibility system is being assembled which will consist of 3 Raytheon RB-25 multioscillator gyros and 3 Bell Aerospace Model XI accelerometers. The instrument cluster will be mounted on a single-degree-of-freedom rotary fixture. Rotation of the cluster will be used to washout long-term error contributors with a Kalman filter using a pseudo-velocity measurement technique.

I. Introduction

Under the sponsorship of the Air Force Geophysical Laboratory (AFGL) the Raytheon Company has contracted to undertake the Latitude and Azimuth System Study (LASS) Program. This program will use laser gyros in a system to experimentally determine the feasibility of simultaneously determining latitude and azimuth to sub-arc second accuracies. An existing ring laser gyro (RLG) inertial measurement unit (IMU) is being modified to a pre-prototype experimental system. To date the analysis and simulation studies indicate that the performance of existing laser gyros are inadequate for achieving sub-arc second accuracies. Laser gyro technology is mature enough to meet precision requirements such as those imposed by the LASS program. A companion paper(1) presents the basics for development of a high accuracy laser gyro suitable for the LASS program. Such a gyro will be developed under independent auspices in 1982. This will give AFGL the option of retrofitting this gyro to the pre-prototype system. The existing system will be used to verify hardware operation, validate software, shakedown calibration procedures and verify the performance analysis approach.

The specific approach for the feasibility system is to make use of a strapdown laser gyro IMU consisting of 3 Raytheon RB-25 multioscillator gyros and 3 Bell Aerospace Model XI accelerometers. The instrument cluster will be mounted on a single-degree-of-freedom rotary fixture. Rotation of the cluster will be used to reduce long-term instrument error contributors. Simultaneous leveling and gyrocompassing will be accomplished with a Kalman filter using pseudo-velocity measurement techniques. An optical transfer system will be incorporated with the instrument cluster.

II. General Requirements

In order to measure astronomic latitude and azimuth, an inertial measurement unit (IMU) must directly or otherwise do the following:

1. Estimate the earth rotation rate vector $\underline{\hat{\omega}}_E$ in a coordinate sysem well defined relative to IMU coordinates;

2. Estimate the force $\underline{\hat{F}}$ opposing local gravity in the same (within tolerance) IMU coordinate system;

3. Find (by computation or physical reorientation of the IMU) local level east in the same coordinate system, as the direction ($\underline{\hat{\omega}}_E \times \underline{\hat{F}}$).

4. Find (co)latitude as the angle between $\underline{\hat{\omega}}_E$ and $\underline{\hat{F}}$.

5. Transmit the latitude and azimuth information to the user accurately, typically transmitting latitude information as a computer output, and transmitting azimuth information via an optical/mechanical reference, e.g., a mirror at known orientation in IMU coordinates.

In addition to the general requirements stated above, the sub-arc second accuracy goal imposes another practical requirement, namely that the gyros used to estimate $\underline{\hat{\omega}}_E$, the accelerometers used to measure $\underline{\hat{F}}$, and the optics (or other mechanical reference) used to transmit azimuth all be rigidly mounted to a common base which has adequate thermal and mechanical stability. Any other configuration would depend on the absolute accuracy of angle read-out mechanisms. Thus, although for convenience it might be desirable to separate the IMU from the outside world by a set of gimbals, the accuracy of the system must not depend on the precision of the

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gimbal angle readings or controls. An important consequence of this is that the IMU must be configured computationally as a strapdown system.

Several fundamentally different options exist for deploying the IMU during the latitute/azimuth measurement, each with different implications for IMU accuracy requirements. The first option is to keep the IMU essentially stationary relative to the earth during the measurement period, with separate calibration maneuvers before and/or after the latitude/azimuth measurement. The second option is to use azimuth reversals and computations to enable simultaneous calibration and measurement of latitude and azimuth. A third option is to use selected rotations and computations such that calibration errors in the IMU are "washed out", so that latitude and azimuth may be found to the desired accuracy in spite of comparatively large IMU calibration errors. The latter option has been selected for implementation and the requirements for design and performance are discussed herein.

III. IMU Stability Requirements For Stationary Mode

Error analysis for the stationary mode is straightforward. Looking first at azimuth, we have

$$\hat{\underline{E}} = \hat{\underline{\omega}}_E \times \hat{\underline{F}}$$

where $\hat{\underline{\omega}}_E$ is the estimated earth rate vector, $\hat{\underline{F}}$ is the estimated force opposing gravity, and $\hat{\underline{E}}$ is a vector in the estimated level east direction. First-order errors in the foregoing are

$$\Delta\hat{\underline{E}} = \Delta\hat{\underline{\omega}}_e \times \underline{F} + \underline{\omega}_e \times \Delta\hat{\underline{F}}$$

Expressing the latter equation in local north, east, down (NED) coordinates,

$\underline{\omega}_E = (\underline{\omega}_e \cos L, 0, -\underline{\omega}_e \sin L)^T$ where

L is the latitude, and $\underline{F} = (0,0,-g)^T$ where

g is the local acceleration of gravity. In these terms, the northerly component of $\Delta\hat{E}$ is

$$\Delta\hat{E}_N = -\Delta\omega_e\, g + \omega_e \sin L\, \Delta F_E$$

The azimuth error is the northerly component of ΔE divided by the magnitude of $\hat{\underline{E}}$ (which is $g\,\omega_E \cos L$), so the azimuth error attributed to incorrect measurements of the earth rate and gravity vectors is (in radian measure)

$$\Delta A = -(\Delta\omega_E/\omega_e) \sec L + (\Delta F_E/g) \tan L$$

For typical continental United States latitudes, we have $\tan L \sim 1.0$, and $\sec L \sim 1.4$. Since 1 arc second is about 5×10^{-6} radians, to get contributions to azimuth error from each error term above to a level of (say) 0.1 arc seconds, we need $(\Delta\omega_E/\omega_e) = 0.35 \times 10^{-6}$ and $(\Delta F_E/g) = 0.5 \times 10^{-6}$.

Since $g \sim 1000$ mgals and $\omega_e = 15°$/hour, there requirements translate into accelerometer bias calibration on the order of 0.5 mgal, and gyro bias drift calibration on the order of 0.000005°/hour.

The astronomic latitude is estimated from the angle between the measured angular rate and the measured force opposing gravity, from one or both of the following:

$$\sin L = \underline{\omega}_e \cdot \underline{F}/(\omega_e g)$$

$$\cos L = |\underline{\omega}_e \cdot \underline{F}|/(\omega_e g)$$

where the first formula is preferable at equatorial latitudes, and the second at polar latitudes. Whichever is used, it is clear from geometric reasoning that, since both earth rate and gravity are in the meridian plane, apart from deflections of the vertical, the angle error is influenced to first order only by the normal meridian plane components of errors in measuring earth rate and gravity.

$$\Delta L = \Delta F_N/g - (\Delta\omega_N \sin L)/\omega_e + (\Delta\omega_D \cos L)/\omega_e$$

Thus, to hold each term contributing to ΔL to (say) 0.1 arc second, we need $\Delta F_N \sim 0.5$ mgals, and $\Delta\omega_N \sim \Delta\omega_D \sim 0.000010°$/hour at temperate latitudes.

Thus, for both latitude and azimuth accuracy requirements, we need gyro stability on the order of 0.000005°/hour and accelerometer stability on the order of 0.5 mgals. These requirements go somewhat beyond the state-of-the-art for long term bias stabilities; however, it is a plausible goal to achieve the requisite stabilities in the short term period encompassing the time required for calibration and latitude/azimuth measurement.

An essential aspect of the calibration not mentioned above is the need for acccurate resolution of the instrument outputs into IMU coordinates. In practical terms, this resolution requires knowledge (to the sub-arc second level) of the instrument axis directions relative to one another, and of the azimuth optical/mechanical reference direction relative to the inertial instrument axes. Fortunately, methods for this kind of calibration have been developed and proven at Raytheon and elsewhere, with errors on the order of 1 arc second for systems using comparatively crude inertial instruments. Complete calibration can be performed in several hours; furthermore, the calibration does not depend on precision test fixtures or set-ups, and therefore can be performed frequently to monitor the mechanical stability of the IMU.

IV. System Simulation and Performance Predictions

Due to the complexity of the proposed system it was necessary to develop a simulation tool to determine the error performance. This digital simulation program will be referred to as NAVNEW.

The NAVNEW simulation program is a covariance error analysis type of program which incorporates the following features:

(1) navigational error equations for a strapdown local level implementation
(2) a Kalman filter for minimizing the estimation error variances
(3) an instrument cluster rotation capability with two options
(4) a laser gyro error model with short and long term instrument errors.

Although gyro and accelerometer quantization error can be simulated in the program these errors are zeroed out under the assumption that the eventual system will have high resolution capability. A high resolution multioscillator ring laser gyro utilizing dual phase locked loops has previously been designed[2]. Based upon extensive testing of the Raytheon RB-25 multioscillator RLG the error model for the gyro is assumed to contain a random walk in angle (short term error) and a first order lag correlated noise process (long term error). The random walk in angle effect is attributed to spontaneous emission in the laser[3]. This gyro noise effect is characterized by Q_θ = angular random walk noise (degrees per root-hour). The long term noise is driven by environmental effects such as temperature variations or temperature gradients and can be characterized by Q_C = correlated noise power (degrees per hour per root-hour) and τ = correlation time (hours). These effects have been quantified in particular RB-25 gyros by using a modified Allan variance statistic[4] for data reduction. Typical values for the random walk in angle noise are Q_θ = 0.002 degrees per root-hour. Where long stretches of data have been available we have gotten long term noise performance of Q_C = 0.005 degrees per hour per root-hour with τ =0.8 hours.

Two options for rotating the complete instrument cluster are available in NAVNEW to investigate their potential for reducing the long term laser gyro error effects. One option allows a continuous azimuth rotation policy at any prescribed rate while the other option provides azimuth reversal capability. With the latter option rotation to any prescribed angle and a return to zero with a fixed dwell time at either extreme can be simulated. In addition the instruments can be placed in any arbitrary orthogonal initial orientation. The results presented in this paper utilize a system with the instrument axes initially aligned to local level coordinates.

The simulation contains a Kalman filter for the estimation of state variable variances. All pertinent errors can be simulated including azimuth and latitude. A full set of local level navigational error equations is implemented and the program has the flexibility to employ a variety of discrete measurement options. In the results presented in this paper we employ a procedure that does not require specific measurements, which we refer to as a pseudo-measurement technique. We use the fact that the system is stationary on the earth as its "measurement". Base motion of the system is simulated by the assignment of a variance to these velocity "measurements" taken at short fixed time intervals, typically every 30 seconds.

The NAVNEW simulation program was exercised to determine the laser gyro performance and the rotation policy requirements needed to achieve sub-arc second azimuth determination with the proposed system. The angular random walk error source of laser gyros is a fundamental error caused by the spontaneous emission phenomenon. This instrument error was examined in an isolated fashion and without rotation. Figure 1 shows azimuth error results for two values of Q_θ,

(a) $Q_\theta = 10^{-4}$ deg per root-hour (Run 240)

(b) $Q_\theta = 10^{-5}$ deg per root-hour (Run 241).

In this run and all others the velocity measurement was used in both the north and east directions every 30 seconds with a variance of 0.01 feet per second. The results of Figure 1 can be adopted as a baseline since the performance cannot be improved beyond that indicated.

The effect of adding long term gyro errors in addition to the short term angular random walk errors is shown in Figure 2 for a choice of $Q_\theta = 10^{-5}$ deg per root-hour. In Run 242 we have added a correlated error with $Q_C = 10^{-3}$ deg per hour per root-hour and τ = 1 hour. Run 242 uses no rotation. A minimum error of 4 arc seconds is achieved in the first hour of operation. The effect of continuously rotating the instrument cluster was investigated in Run 243 of Figure 2 for a rotation rate of 15 degrees per second. The results predict sub-arc second performance at a level of approximately 0.8 arc second. Runs made with a higher rotation rate indicate that rates equal to or greater than 15 degrees per second give the same performance as Run 243.

The design of a rotary fixture is complicated for a continuous rotation policy (i.e. slip rings required), thus another option was investigated. This alternate policy was a rotation from zero to 360 degrees and back to zero cyclically with no dwell time at the extremes. This policy was tried in Run 245 of Figure 3 at a maximum rotation rate of 15 degrees per second. Run 245 is seen to conform with Run 243 for continuous rotation and justifies a 0°-360°-0°... rotary fixture design for the LASS system.

The simulation results of the feasibility analysis have indicated a laser gyro angular random walk performance requirement of 10^{-5} deg per root-hour to achieve sub-arc second azimuth error determination. Laser gyros with this capability do not currently exist. On a concurrent Air Force contract[1] Raytheon has contracted to design a multioscillator gyro with an angular random walk capability equal to or better than 10^{-4} deg per root-hour. The design will be based upon recent theoretical investigations at Raytheon[3,5] and new concepts of block design which allow large path lengths in compact form factors. This gyro design will be available in 1982.

V. LASS System Description

The LASS system is being configured by modifying a brassboard laser gyro IMU being fabricated for aircraft usage. This IMU will be housed in a full ATR configuration and will use Raytheon RB-25 Mod II multioscillator ring laser gyroscopes[2] and Bell Aerospace Model XI accelerometers. The RB-25 Mod II RLG has been developed over the past two years under contract with WPAFB on its Ring Laser Gyro Technology for Advanced Aircraft Program [4]. Two brassboard units scheduled for delivery to WPAFB in October 1981 are currently undergoing preliminary performance tests. Three additional RB-25 Mod II RLGs will be fabricated for use in the LASS system by the end of November 1981. About a month will be required to integrate the gyros into the IMU in readiness for the LASS experimental tests early in 1982.

Current expected performance for the RB-25 Mod II gyro (Figure 4) is summarized below:

- Random walk in angle $<0.002°/\sqrt{hr}$.
- Random drift (long term) $<0.003°/hr/\sqrt{hr}$.
- Day to day (turn-on to turn-on) = 0.003°/hr.
- Drift thermal sensitivity = TBD
- Scale factor linearity <0.6 PPM
- Scale factor stability <2.5 PPM
- Scale factor thermal sensitivity <0.1PPM/°F
- Reaction time = 0.3 second.

It can be seen that the performance of the gyro will not allow sub-arc second azimuth performance. No current laser gyro will meet the LASS requirements. Raytheon has recently initiated a program[1] for design of a laser gyro which will approach or better an azimuth accuracy of 1 arc second. The design is to be completed in 1982. In the interim the LASS program will proceed with the RB-25 Mod II gyro in order to verify hardware operation, validate software, shakedown calibration procedures and to verify the performance analysis approach reported here. If all goes well AFGL will have the option of retrofitting the high accuracy ring laser gyro into the LASS system.

Figure 5 shows an exploded isometric view of the full ATR system with its rotary drive. The rotary azimuth fixture (RAF) can be both indexed in 90° increments or continuously rotated to 360° and back to zero. Measurements at the 0° and 180° positions will allow gyro bias calibration and the rotation policy will be used to reduce long term errors when used in conjunction with the Kalman filter software.

Figure 6 shows the IMU in its full ATR configuration with electronics modules in the forefront. The rotary drive system (Figure 7) can be easily removed from the ATR box by removal of one cover and the disconnect of one cable. Figure 8 shows the Bell XI accelerometer triad and the accelerometer pulse rate converter (PRC) electronics. The accelerometer triad is housed in the hollowed-out structure used for mounting the ring laser gyros (see Figure 5).

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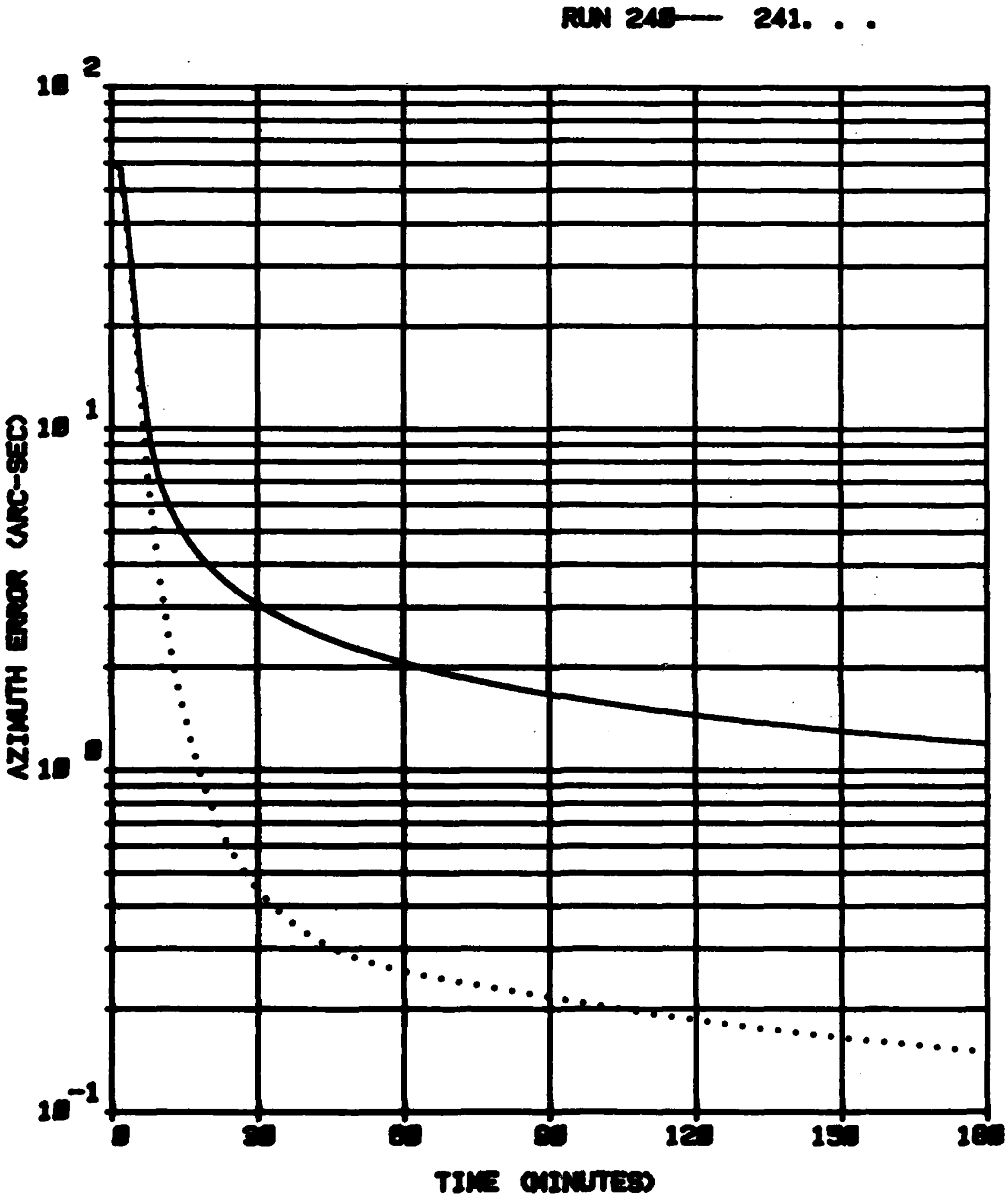

Figure 1. Effect of Angular Random Walk on Azimuth Alignment Performance

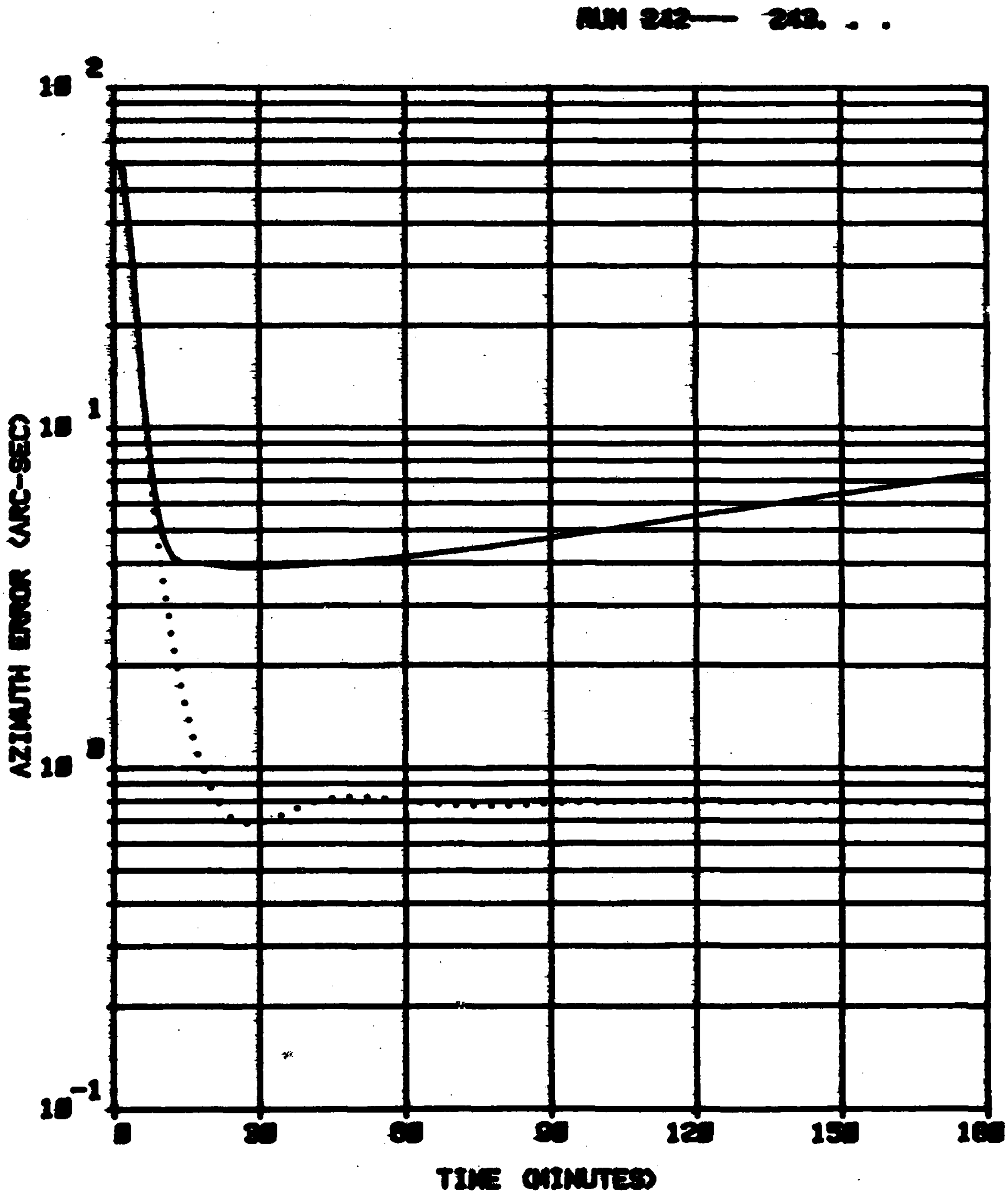

Figure 2. Combined Effect of Short and Long Term Gyro Errors with and without Continuous Azimuth Rotation

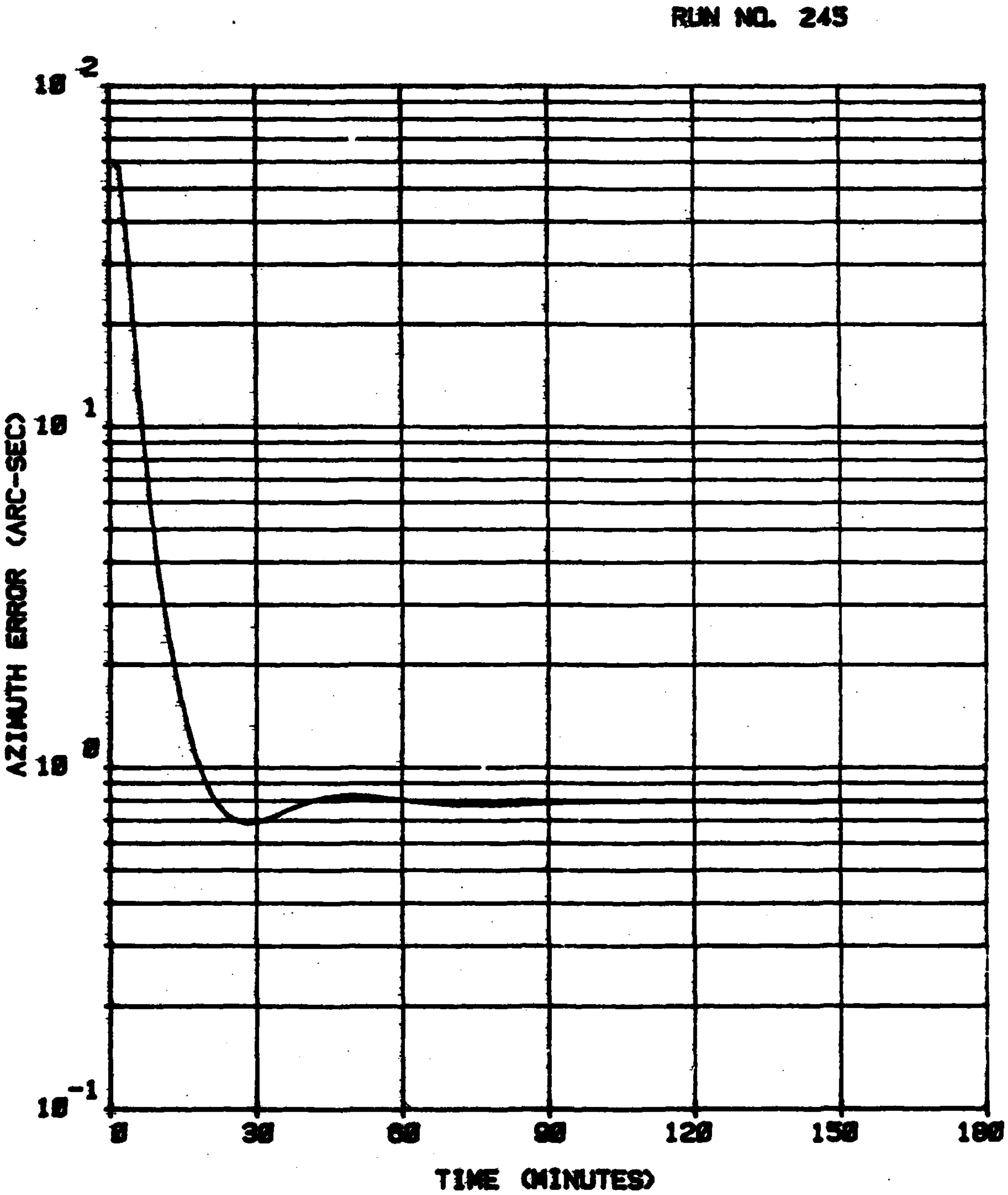

Figure 3. Combined Effect of Short and Long Term Gyro Errors with 360° Azimuth Reversals

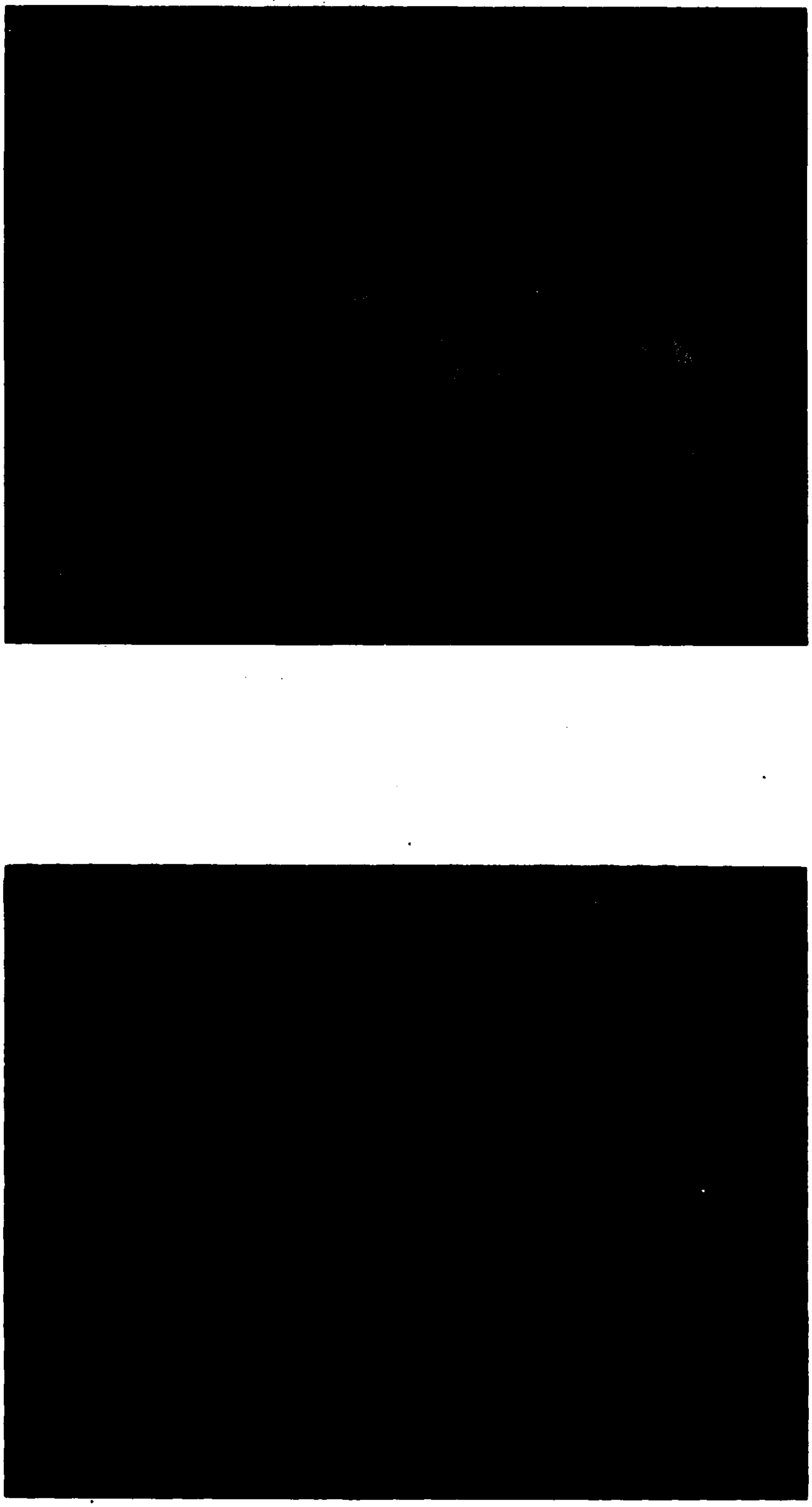

Figure 4. Raytheon RB-25 Ring Laser Gyro Hardware and Electronics

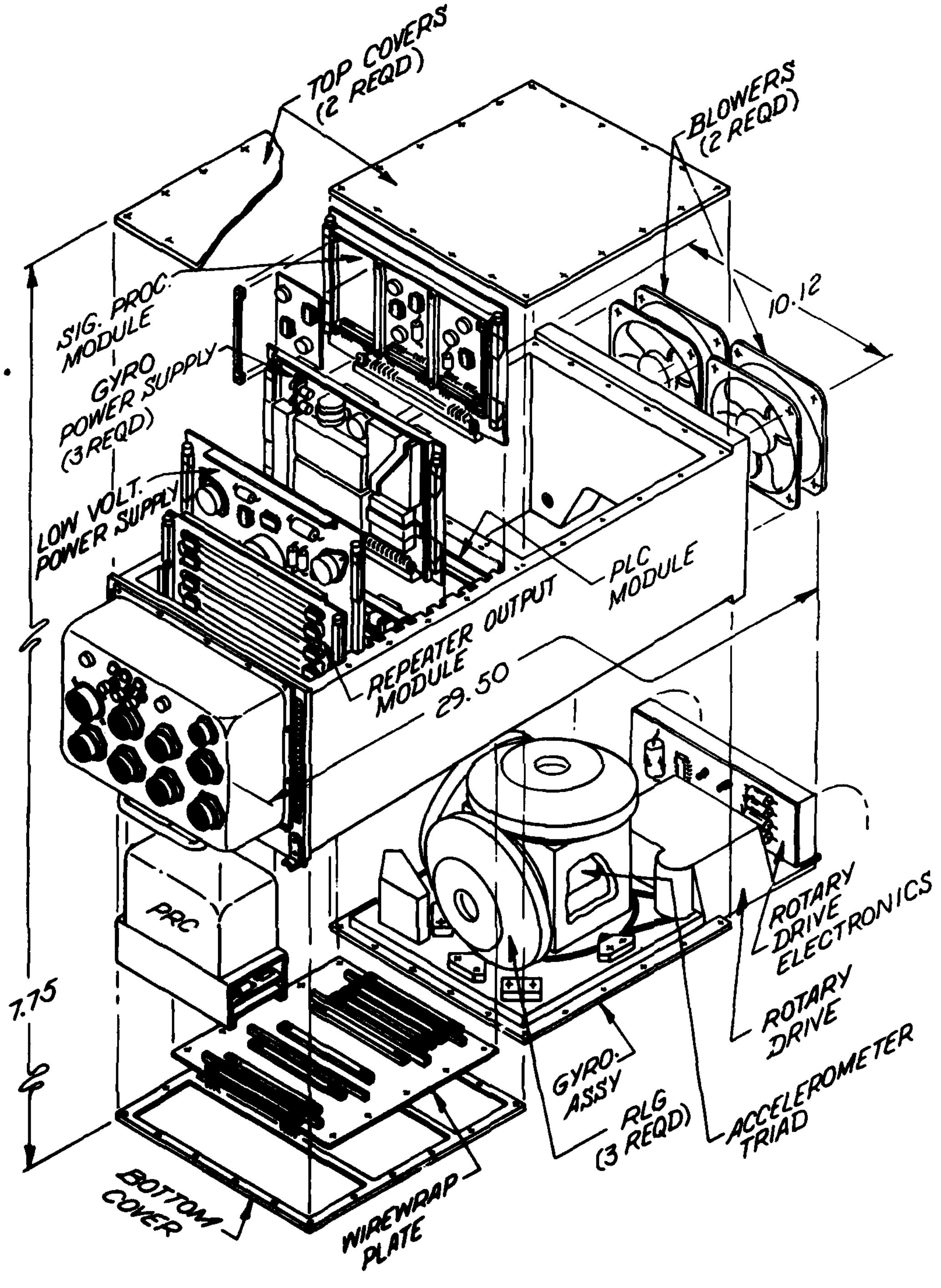

Figure 5. Laser Gyro IMU Assembly

Figure 6. Full ATR Brassboard IMU and Electronics Modules

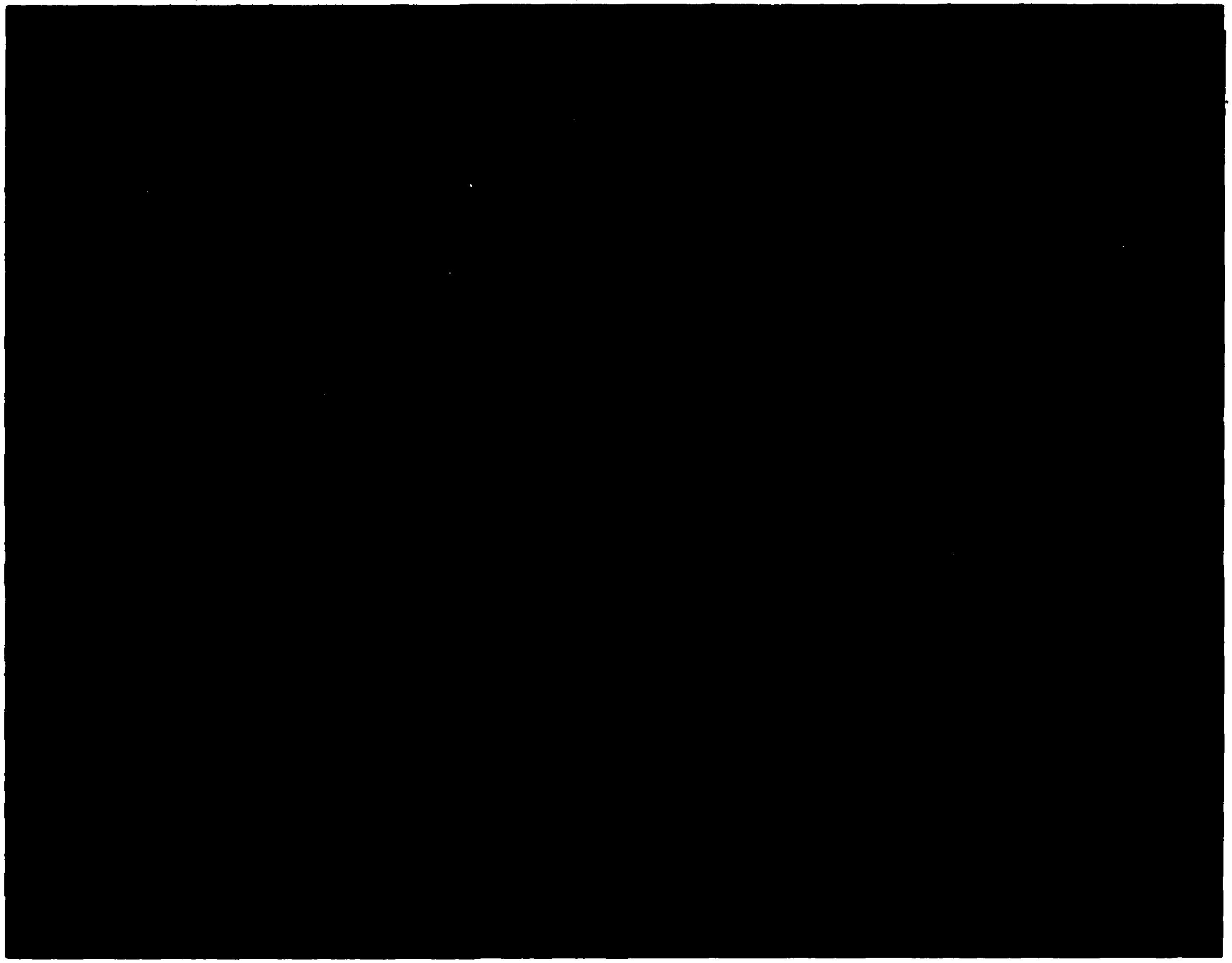

Figure 7. Rotary Drive System

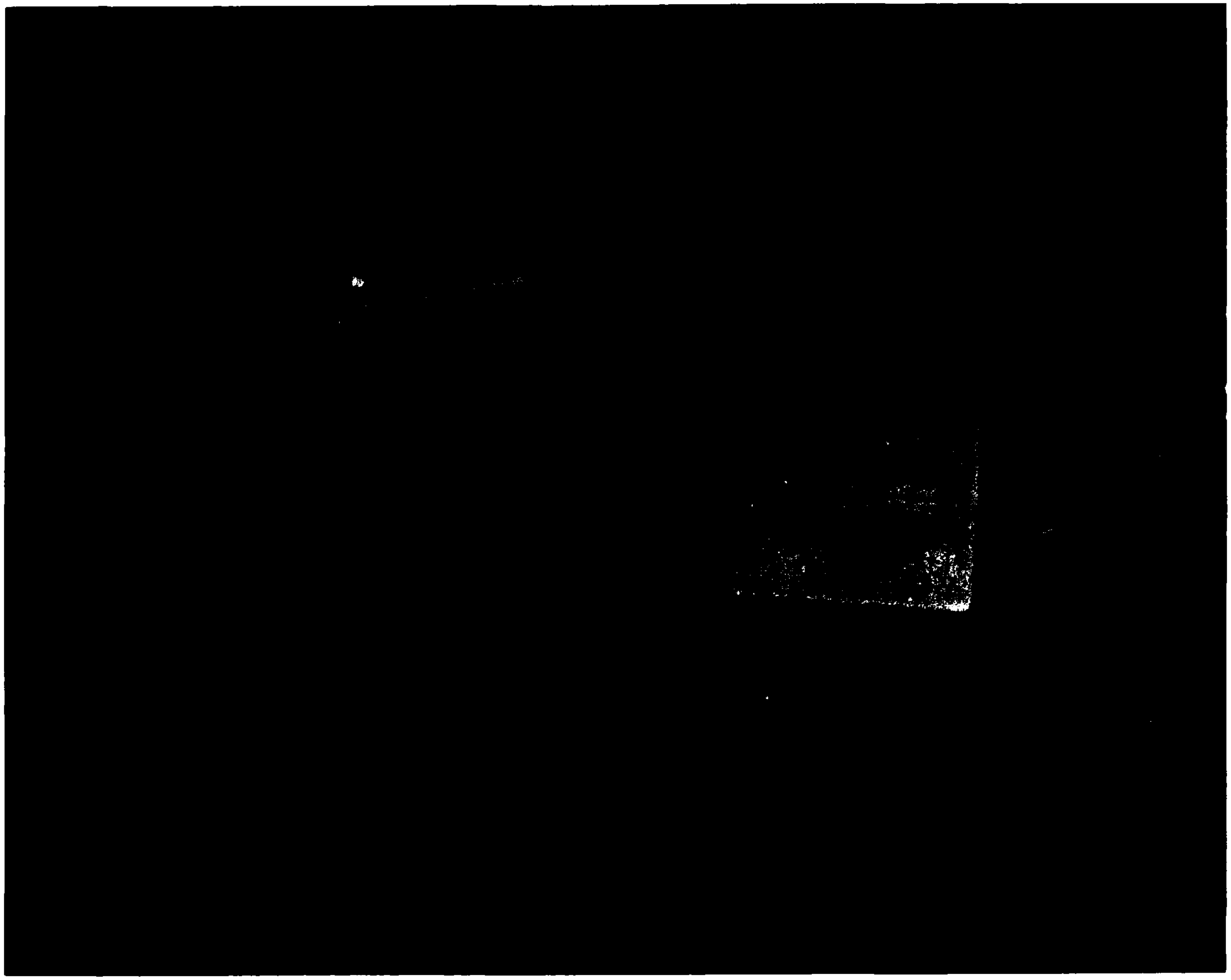

Figure 8. Bell Aerospace Model XI Accelerometer System and PRC